Cold Regions Research and Engineering Laboratory

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Measurement of Lateral Tire Performance
on Winter Surfaces

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Abstract: Extending two-dimensional models of tire–vehicle interaction to full three-dimensional functionality requires an understanding of lateral forces on off-road terrain and low-friction surfaces. Experiments were conducted at the Nevada Automotive Test Center using two principal tires—an all-season LT235/75R15, which has been the subject of many tests on the CRREL Instrumented Vehicle (CIV), and a tire used on the military's HMMWV, size 37X12.50R16.5—on ice, packed snow, and disaggregated snow. The tests showed that the lateral coefficient of friction for both tires increases rapidly with slip angle from zero slip angle. For the packed and disaggregated snow surfaces, the lateral coefficient of friction appears to asymptotically approach a maximum value with increasing slip angle to slip angles of approximately 15 degrees. For the ice surface, the initial behavior is similar, but the peak lateral coefficient of friction is reached at low slip angles, normally 2-4 degrees, and then the lateral coefficient of friction falls off significantly. With respect to peak lateral friction coefficients, the two tires behave similarly on each surface with one exception: on ice the HMMWV tire develops peak values approximately 50% of those generated by the CIV tire. Tire pressure impacts were not significant, but the trends were for higher lateral traction with lower tire pressures.

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Unit Conversion Factors

Multiply	By	To Obtain
inches	0.0254	meters
miles per hour	0.44704	meters per second
pounds (force)	4.448222	newtons
pounds (mass)	0.45359237	kilograms

1   Introduction

The Army has approved and funded an Army Technology Objective (ATO) entitled "High Fidelity Ground Platform and Terrain Mechanic Modeling." This ATO is being performed by the Engineer Research and Development Center (ERDC) along with the U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC) and the Army Research Laboratory (ARL). Two ERDC laboratories are participating in the ATO: the Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH, and the Geotechnical and Structures Laboratory (GSL) in Vicksburg, MS.

One of CRREL's major milestones for the ATO is to extend two-dimensional ground contact models for the TARDEC Real-time Simulator to full three-dimensional functionality by including the lateral forces. Central to that requirement is an understanding of lateral forces on all-seasons terrain. While modeling of vehicle tire lateral force interactions for typical hard-paved surfaces is well understood, there is a need to translate that understanding in a consistent manner into off-road terrain and low-friction surfaces. The experimental work described in this paper is fundamental to gaining the required understanding for undriven wheels.

2   Background

In modeling tire–terrain interaction, it becomes difficult to separate the effects attributable to the tire from those attributable to the terrain, and indeed some effects are synergetic and may be rightly associated with a particular tire/terrain combination. A number of models have been proposed that treat the lateral force relationships for a free-rolling wheel (as opposed to a driven wheel) that is our principal interest here. Neglecting the interaction with the terrain, the tire alone, owing largely to its construction and inflation, is an extremely complicated component that defies a rigorous yet simple analytical treatment. Hence tire modeling has progressed to a high degree of sophistication with respect to both analytical and empirical approaches. Pacejka (2002) breaks down the approaches into four categories:

- Experimental based. Data from full-scale tire tests are fit to complex empirical models such as the well-known Magic Formula (Pacejka 2002) by means of regression analysis.
- Similarity based. Basic empirical relationships are used to interpolate/ extrapolate performance at conditions not measured or for other tire parameters.
- Simple physical models. Based on simple first-principles mechanical representations, these models necessarily make simplifying assumptions in order to provide an analytical treatment.
- Complex physical models. These models use methods such as finite elements to account for many complications and inhomogeneities of tire construction and interaction with terrain.

For high-speed, real-time simulation on varied terrain, the complex empirical and the complex physical models are impractical. The former cannot operate outside of well-defined tire–terrain datasets, and the latter require excessive computational resources. Simplified physical models might fail to capture the complex tire–terrain interaction of winter surfaces. While "similarity-based" solutions would not in-and-of-themselves serve our purpose, as there is little existing data from which we could confidently extrapolate, they can provide a framework for regression analysis of the experimental data. We feel that the data gathered in this study can be of use not only in identifying suitable methods for treating high-speed, real-time simulation on varied terrain, but also for verifying each of the tire modeling approaches discussed above.

3 Description of Test Program

To span the range of winter surfaces that might be encountered, our desire was to test on three surface types: ice, packed snow, and fresh (unconsolidated) snow. This need ruled out the use of laboratory testing apparatus normally used for lateral testing of tires. Towed or truck-mounted single-wheel testers would have suited our needs, but instrumented vehicles provided a more economical solution. The work reported here was accomplished via a contract with the Nevada Automotive Test Center (NATC) using their instrumented vehicles, as will be described below.

While ideally we would have liked to test a number of different tires, funding limitations forced us to greatly restrict the number chosen. Given the target audience for our modeling efforts, the tire in use on the Army's High Mobility Multipurpose Wheeled Vehicle (HMMWV) was an obvious choice. The example of this tire that we used was a 37X12.50R16.5 Goodyear MT.

We chose the LT235/75R15 Goodyear Wrangler HT as the second tire. It has been extensively tested on our CRREL Instrumented Vehicle (CIV) (Blaisdell 1985).

Data are also included on two other tires that were not the principal focus of the testing but for which some data were collected. The first of these is the NATC Standard Reference Test Tire (SRTT), which is used as a course monitoring tire by NATC. This tire is a P195/75R14. The second tire was a passenger car tire, size 225/50R18.

The tests described here were conducted over the course of the 2004 and 2005 winter testing seasons. Most tests were conducted at NATC's winter testing facility at West Yellowstone, Montana. The tests on an ice surface were conducted at an ice arena in Butte, Montana. In addition to varying the tire and surface, inflation pressure was also varied; Table 1 summarizes the tests conducted. The tires were all tested at typical normal operating loads. The CIV tire was tested at 1400 lbf normal load, the HMMWV tire at 2,500 lbf normal load, the NATC-SRTT at 1,030 lbf normal load, and the passenger car tire at 1,250 lbf normal load. For the packed snow surface, some tests were performed in each of the two seasons (Table 1). The condition of the surfaces for the tests is summarized in Table 2.

Table 1. Tire/surface test matrix.

Tire	Surface	Lateral or longitudinal	Tire pressures (kPa)
CRREL Instrumented Vehicle (LT235/75R15)	Ice	Lat. & Long.	97, 152, 283
	Packed snow, 2004	Lat. & Long.	97, 152, 283
	Packed snow, 2005	Lat. & Long.	179, 241
	Disaggregated snow	Lat. & Long.	179, 241
HMMWV (37X12.50R16.5)	Ice	Lat.	138, 207, 310
	Packed snow, 2005	Lat. & Long.	138, 310
	Disaggregated snow	Lat. & Long.	138, 310
NATC-SRTT (P197/75R14)	Ice	Long.	241
	Packed snow, 2004	Long.	241
	Packed snow, 2005	Lat. & Long.	241
	Disaggregated snow	Lat. & Long.	241
Passenger Car (225/50R18)	Packed snow, 2005	Lat. & Long.	241
	Disaggregated snow	Lat. & Long.	241

Note: For the CIV and HMMWV tires, with one exception, for each condition above, both lateral and longitudinal traction test data were obtained. For the HMMWV tire on ice, the longitudinal test data had to be rejected.

Table 2. Surface specifications.

Surface	Density (g/cm³)	Air temperature (°C)	Surface temperature (°C)
Ice	—	7.2	−1.7
Packed snow, 2004	0.44	−0.6	−1.7
Packed snow, 2005	0.51	−7.8	−9.5
Disaggregated snow	0.41	2.7	−3.1

Note: The "Surface Temperature" was measured at 2.5 cm below the surface for the snow surfaces and on the surface for the ice surface.

The original test objective was to include ice, packed snow, and fresh snow as test surfaces. Despite testing over nearly a month in the combined 2004 and 2005 seasons, fresh snow was never received in sufficient quantities for a meaningful test. We had wanted to test the tires on fresh snow beause it is a highly deformable winter surface. The lack of cooperation from the prevailing weather caused us to resort to the alternative of "disaggre-gating" snow that had been previously packed to achieve a highly deform-able snow surface. The snow was disaggregated by six passes of a snow

groomer, as shown in Figure 1. While this resulted in a material with a higher density than would be expected for fresh-fallen snow (Table 2), it did exhibit a high degree of deformation during the testing, as can be seen from the ruts of a lateral traction test of the HMMWV tire shown in Figure 2. The maximum rut depth for the lateral traction tests in the disaggregated snow was approximately 3.5 cm for the HMMWV tire and 4.0 cm for the CIV tire.

Figure 1. Disaggregating snow with the snow groomer.

Figure 2. Rut in disaggregated snow from a lateral traction test of the HMMWV tire.

4   Tests Vehicles and Test Procedures

Longitudinal Traction

For the longitudinal traction tests, the Dynamic Force Measurement Vehicle (DFMV)-10 or DFMV-12, described in detail later, is driven onto the prepared test course and the speed stabilized at a predetermined initial speed. When the ground speed is stabilized, a start button is depressed, actuating the on-board data acquisition and analysis computer and starting the throttle actuator. The operator, viewing a ground speed indicator, gradually applies brakes to the non-test wheels to maintain a constant ground speed. This process is repeated for at least twelve spin-ups for each control and test tire. The SRTT (Standard Reference Test Tire) was used as a control tire to validate the surface condition.

The data are logged by the on-board computer as each tire is tested. The computer displays the data from these twelve spin-ups, allowing the operator to review the data and determine if more runs are required to satisfy the test requirement of standard deviation and coefficient of variation. After completion of that tire's test, the data are printed in a Tire Summary showing the data by run, a statistical analysis of those data, the runs cast out (discussed later in *Data Processing*), and a tractive μ versus slip velocity tabular analysis. A normalized μ-slip curve is also graphed.

The test tire pressure is then adjusted or the next tire in the test sequence is installed. For a multiple tire test, the sequence of control–test–test–control is followed. In accordance with established NATC test methodology, the tire pressures are checked and adjusted as required throughout the test operations.

Dynamic traction data are collected and processed using the Dynamic Tire Force Measurement Suite (DTFM Suite). The test data are processed in terms of tire coefficient (μ) in dynamic traction at peak μ and at established intervals of differential interface velocity (DIV). For each tire at least twelve spin-ups are made, and data are collected by the computer. Each run (twelve spin-ups) is processed using the two methods described below:

1. ASTM average μ: An average μ is calculated for the data between the slip velocities of one and fifteen miles per hour.

2. Peak μ: The average maximum μ for the run is determined.

For each method an average value and coefficient of variation is calculated for all runs collected. Any spin-up with a value exceeding a coefficient of variation of 5% is thrown out. The tire coefficient, or μ (mu), is a value used to define the actual frictional characteristic of the tire on the surfaces tested. The following formula defines the dynamic μ:

μ = Tire Tractive Force / Tire Vertical Load.

The differential interface velocity (DIV) defines the relationship between wheel speed and vehicle ground speed and is an expression of wheel slip:

DIV(mph) = Wheel Speed(mph) – Ground Speed(mph).

These results are then compiled into a summary showing a statistical analysis of those data, a tractive μ vs. DIV table, and a graph of the tractive μ vs. DIV.

Dynamic Lateral Traction

The test vehicle is driven onto the prepared test course with the test tire on the left rear of the test vehicle. The ground speed is held at a constant, pre-determined velocity. When the ground speed is stabilized, the hydraulic valve controlling the articulated right rear tire angle is actuated, and the data acquisition system is activated (Fig. 3). The operator, viewing a ground speed indicator, maintains the ground speed and steers the vehicle in a straight line down the course. The test tire is instrumented for load measurement (Fig. 4). Vehicle yaw is measured progressively from 0 to 15° slip angle via a pivot-mounted fifth wheel and string potentiometer. The yaw rate of the vehicle is approximately 7 degrees per second for Dynamic Force Measurement Vehicle (DFMV)-8 and 20 degrees per second for DFMV-9. The slip angle is then returned to zero. This procedure is repeated at least twelve times for each control tire and test tire/test condition.

As each variable is subjected to the test sequence, the data are logged by the on-board computer. The computer displays the data from these twelve runs, allowing the operator to review the data and determine if more runs are required to satisfy the test requirements of maximum coefficient of variation. After completion of that test, the data are printed in a summary

showing the data by run, a statistical analysis of that data, the runs cast out, and a lateral µ vs. slip angle (alpha) tabular analysis. A normalized µ-alpha curve is also graphed and printed. The test tire is then changed and the run sequence repeated for the next variable.

Figure 3. Articulated wheel (right).

Figure 4. Measurement wheel (left).

The lateral friction coefficient, or μ, is a value used to define the actual frictional characteristic of the tire on the surfaces tested. The following formula defines μ:

Lateral μ = Lateral (Side) Force/Vertical Load.

Test data are recorded in lateral friction coefficient in dynamic lateral traction vs. slip angle. The slip angle (α) is the angle formed between the wheel angle and the vehicle travel path. The vehicle yaws to a maximum of 15 degrees, and a slip angle of 8.0 degrees is selected to adequately define the μ vs. α profile of a test variable. The α calculation is irrespective of ground speed and is printed in a summary showing a statistical analysis of that data, a lateral friction coefficient μ vs. α table, and a graph of the lateral friction coefficient μ vs. α curve. All lateral μ vs. α data are based on a binned average with a bin size of 0.3° α.

Test Vehicles

The NATC passenger car and light truck traction vehicle, known as DFMV-10, is used for longitudinal traction and braking traction studies for tire sizes ranging from 13 to 16.5 inches. The vehicle system is capable of wheel slip velocity measurements of up to 25 mph with tire loads from 470 to 4,000 pounds per tire. The DFMV-10 is a GMC K-1500 pickup truck with the following specifications/modifications:

- 350 CID V-8 engine

- Turbohydramatic 700R4 transmission

- 4,000-pound axles, 4.10:1 ratio

- Modified New Process 205 transfer case, 2.25: 1 ratio

- Modified rear suspension with:

  – Parallel control arms to eliminate transducer angular changes

  – Air springs for infinitely variable ride heights

  – Hubs adaptable for 13- to 16.5-inch tire sizes

- Extended cab to allow for installation of complete on-board computerized data analysis

- Braking system gated for stopping any or all wheels

- Cog-belt-driven speed transducers at each wheel end

- Time versus force throttle actuator
- NATC Wheel Force System:
    - 4,000-pound wheel force transducers measuring on vertical, longitudinal, and lateral axes at each rear axle end
    - Integrated visual readout (one)
    - Zero force DIV calibration
- On-board air system for adjusting air springs for test weight.

The NATC passenger car and light truck traction vehicle, DFMV-8, is used for lateral traction studies for tire sizes ranging from 13 to 16.5 inches. This vehicle system is capable of slip angle measurements of 15 degrees with tire loads from 670 to 2,400 pounds per tire. The DFMV-8 consists of a J-3000 Jeep pickup truck with the following specification/modifications:

- 360 CID V-8 engine
- Turbohydramatic T400 transmission
- 4,000 pound axles, 4.10:1 ratio
- Modified Dana 20 transfer case, 2.20: 1 ratio
- Modified rear suspension with:
    - Parallel control arms to eliminate transducer angular changes
    - Air springs for variable ride heights
    - Hubs adaptable for 13- to 16.5-inch tire sizes
    - Lateral track bar
- Braking system gated for stopping any or all wheels
- Cog-belt-driven optical encoder at each wheel end
- Time versus force throttle actuator
- NATC Wheel Force System:
    - 6,000-pound wheel force transducers measuring on vertical, longitudinal, and lateral axes at each rear axle end
    - Integrated visual readout (two)
    - Zero force DIV calibration

- Dual batteries and dual alternators, isolating the vehicle and instrumentation electrical supply systems.

DFMV-9, the NATC medium-duty traction vehicle is used for longitudinal and lateral traction studies for tire sizes ranging from 16.5 to 24.5 inches. The vehicle system is capable of wheel slip velocity measurements up to 15 mph with tire loads from 2,500 to 10,000 pounds per tire. The DFMV-9 consists of a GMC cab-over semi-tractor with the following specifications/modifications:

- 427 CID gasoline engine
- Allison MT 540 5-speed automatic transmission
- Modified rear suspension with:
  - Four-bar parallel link suspension
  - Air springs
  - Selective wheel drive
  - Ten bolt hubs for tire sizes from 16.5 to 24.5 inches
- Priority braking system for any or all wheels
- Cog-belt-driven shaft encoders at each wheel end
- NATC wheel force system
  - 10,000-pound wheel force transducers measuring longitudinal, vertical, and lateral forces at left rear axle end
  - Integrated readout for individual forces or function force
  - Zero force DIV calibration.

The DFMV traction test vehicle measures and records the dynamic vertical, longitudinal, and lateral forces at the tire/ground interface, as well as wheel speed and ground speed. The force measurements are accomplished through non-rotating tri-axial load cells located at the wheel ends of the rear axle of the vehicle. Each tri-axial load cell axis has 28 strain gages mounted on a proving ring that is calibrated for forces up to 4,000 or 6,000 pounds. The speed measurements are accomplished through optical shaft encoders mounted on the test wheel and a reference non-test wheel.

The DFMV-12 is the NATC medium-duty traction vehicle used for dynamic driving traction studies for tire sizes ranging from 16.5 to 24.5 inches. The

vehicle system is capable of wheel slip velocity measurements up to 15 mph with tire forces from 2,500 to 10,000 pounds per tire. The GMC cab-over semi-tractor has the following specifications/modifications:

- 454 CID gasoline engine

- Allison 540 5-speed automatic transmission

- Modified rear suspension with:
  - Four-bar parallel link suspension
  - Air springs
  - Selective wheel drive
  - Ten bolt hubs for tire sizes from 16.5 to 24.5 inches

- Priority braking system for any or all wheels

- Cog-belt-driven shaft encoders at each wheel end

- NATC wheel force system
  - 10,000-pound wheel force transducers measuring longitudinal, vertical, and lateral forces at left rear axle end
  - Integrated readout for individual forces or function force
  - Zero force DIV calibration.

The DFMV traction test vehicle measures and records the dynamic vertical, longitudinal, and lateral forces at the tire/ground interface, as well as wheel speed and ground speed. The force measurements are accomplished through non-rotating tri-axial load cells located at the wheel ends of the rear axle of the vehicle. Each tri-axial load cell axis has 28 strain gages mounted on a proving ring that is calibrated for forces up to 10,000 pounds. The speed measurements are accomplished through optical shaft encoders mounted on the test wheel and a reference non-test wheel.

Test Instrumentation

For the DFMV-8 and DFMV-9, a MEGADAC 3000 series digital data acquisition system was utilized to record raw data during the lateral and longitudinal traction testing. The MEGADAC system is a 16-bit acquisition system capable of recording 512 channels simultaneously with an aggregate sampling rate of 25,000 samples per second. Data were initially captured at 100 samples per second and low-pass filtered at 20 Hz.

The DFMV measures and records the dynamic vertical, longitudinal, and lateral forces at the ground interface. Wheel speed, ground speed, and slip angle are also measured. The force measurements are accomplished through non-rotating tri-axial load cells located at the wheel ends of the rear axle of the vehicle. Each tri-axial load cell has 28 strain gages mounted on a proving ring that is calibrated for forces up to 4,000 pounds.

Optical encoders (1,000 counts/revolution) are used for the wheel velocity and ground speed (wheel end) measurements. The encoders are mounted at each rear wheel and are driven by the timing belt. The speed sensor is calibrated through a known-distance speed trap using a Philips digital counter. These counts per mile are then used to set the frequency-to-voltage converter. The speed sensor is calibrated in miles per hour.

The on-board DFMV instrumentation system consists of the following:

- Data acquisition and processing system:
    - MegaDAC digital data acquisition system
    - Real-time display of forces, angles, and speeds via notebook computer
- NATC-DFMV wheel force system:
    - Tri-axial 10,000 pound wheel force transducer on the left rear wheel measuring on vertical, longitudinal, and lateral axes
    - Integrated visual readout
    - Zero force calibration.

The instrumentation for the DFMV-10 is the NATC tire test acquisition system, the portable MuCase. It is mounted during testing in the curb side of the vehicle. An isolated power supply from an auxiliary alternator is used to provide constant uninterrupted voltage to the computer and instrumentation.

The DFMV utilizes a MuCase data acquisition and processing system that consists of:

- IOTECH Daqbook 2000 data acquisition system with the following attributes:

- 16 channel, 16 bit AID converter
- 100 KHZ aggregate burst acquisition
- ±10 V range
- 2 10-MHZ counters (wheel and ground speed)
- Parallel interface
- Embedded PC with the following attributes:
  - Pentium 1.2 GHZ processor
  - 512 MB RAM
  - 30 GB hard drive
  - Compact flash interface for non-volatile data storage and backup
  - 1024 x 800 SVGA interface with 15 inch LCD flat panel monitor
  - Flexible keyboard
  - Glidepoint touchpad pointing device
  - Windows XP Professional
  - Running NATC DFMV 2000 data acquisition and processing software
- Signal conditioner with the following attributes:
  - Instrumentation amplifier with 250 gain, common mode rejection, and low pass filtration
  - 5-V excitation
  - Automated shun calibration system (computer controlled)
  - 5-V excitation for ShafEncoder inputs
- Throttle control system with the following attributes:
  - 5-V power with heavy duty RC rated servo
  - Fail safe and over-current protection
  - Manual or computer control of ramp, offset
- Power distribution and filtration
- Mil-Std military style Bendix input connectors for power, signals, throttle control
- NATC-DFMV wheel force system:

- Tri-axial 10,000-pound wheel force transducer on the left rear wheel measuring on vertical, longitudinal, and lateral axes

- Integrated visual readout

- Zero force calibration.

Data Processing

The analog-to-digital system is an IOTech Logbook 2000. The computer receives the 500-Hz digital signal and performs a five-point moving average calculation, resulting in approximately 100 samples per second. The raw data are recorded in a raw data file. Real-time processing tools bin the data in 0.3 DIV bins for analysis of the mu-slip relationship and real-time mu-slip display. These data are stored in a processed data file. The final DIV data are used to close the control loop of the automated throttle control to assure that 15 DIV (300% slip) is reached. A low-pass 20-Hz filter is utilized during post-processing.

For both systems a minimum of 12 spins are conducted for each tire, and spins with a coefficient of variation greater than 5% are removed from the test matrix. These spins can either be deleted and rerun by the vehicle operator during the test, or kept, in which case the spins are automatically cast out by the program in the calculation of final test results. The high and low spins (based upon peak μ) were discarded until the coefficient of variation was less than 5%. The coefficient of variation is defined as the standard deviation divided by the mean. A minimum of five spins or yaws is required to calculate the final test results.

Instrument Calibration

All applicable instrumentation utilized for this test program was calibrated in accordance with NATC calibration procedures, and records are maintained on file. The instrumentation will yield sensor data within a ±3% accuracy.

5   Test Results

The principal focus of the test results reported here are the lateral traction measurements. However, for each combination of surface/tire/inflation pressure, longitudinal traction tests were also conducted. A typical set of longitudinal traction test results is included in Figure 5. The results of the longitudinal traction tests are summarized in Table 3 for the two test standards described earlier.
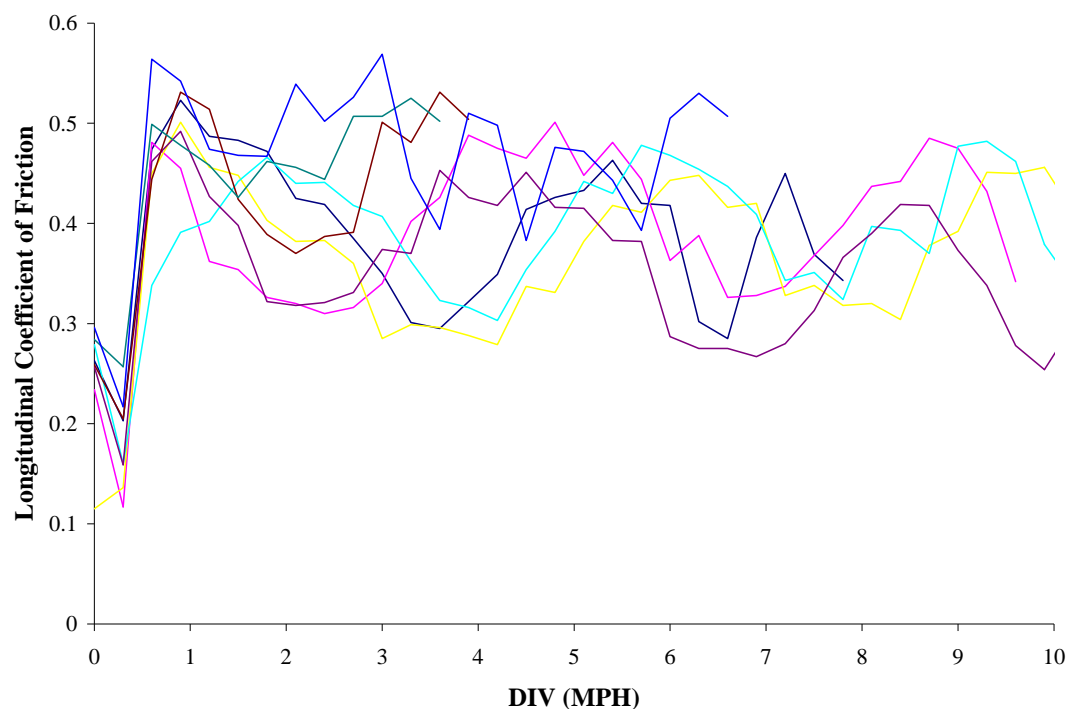

Figure 5. Composite of the eight individual longitudinal traction tests contributing to the dataset for the HMMWV tire on 2005 packed snow at 138-kPa inflation.

Table 3. Longitudinal traction test results.

Tire	Surface	Pressure (kPa)	Longitudinal traction coefficient	
			Peak	ASTM average
CIV	Ice	97	0.12	0.07
		152	0.11	0.08
		283	0.11	0.07
	Packed snow, 2004	97	0.38	0.30
		152	0.38	0.29
		283	0.33	0.25
	Packed snow, 2005	179	0.37	0.28
		241	0.35	0.26
	Disaggregated snow	1796	0.26	0.19
		241	0.22	0.16
HMMWV	Packed snow, 2005	138	0.52	0.41
		310	0.46	0.37
	Disaggregated snow	138	0.55	0.44
		310	0.38	0.30
NATC-SRTT	Ice	241	0.10	0.06
	Packed snow, 2004	241	0.45	0.36
	Packed snow, 2005	241	0.37	0.32
	Disaggregated snow	241	0.21	0.16
Passenger car	Packed snow, 2005	241	0.33	0.21
	Disaggregated snow	241	0.18	0.09

Note: The longitudinal test data for the HMMWV tire on ice had to be rejected.

Figure 6 shows a typical set of results for a tire/pressure/surface test combination for the lateral traction tests. Each curve represents an individual test, the results of which are binned and then averaged as described earlier, the averaged result for this set of tests being shown in Figure 7. In general, the tests on the ice surface showed less test-to-test variation than the tests on snow, as can be seen from comparing Figures 6 and 8. Figure 9 shows the averaged result for the tests on ice. A summary of the maximum values from all the lateral traction tests is provided in Table 4; the standard deviations about the mean values are also included in Table 4. This information is shown graphically in Figures 10 and 11 for the CIV and HMMWV tires, respectively. Figure 12 presents the maximum lateral coefficients for all the tires on the 2005 packed snow and disaggregated snow surfaces.
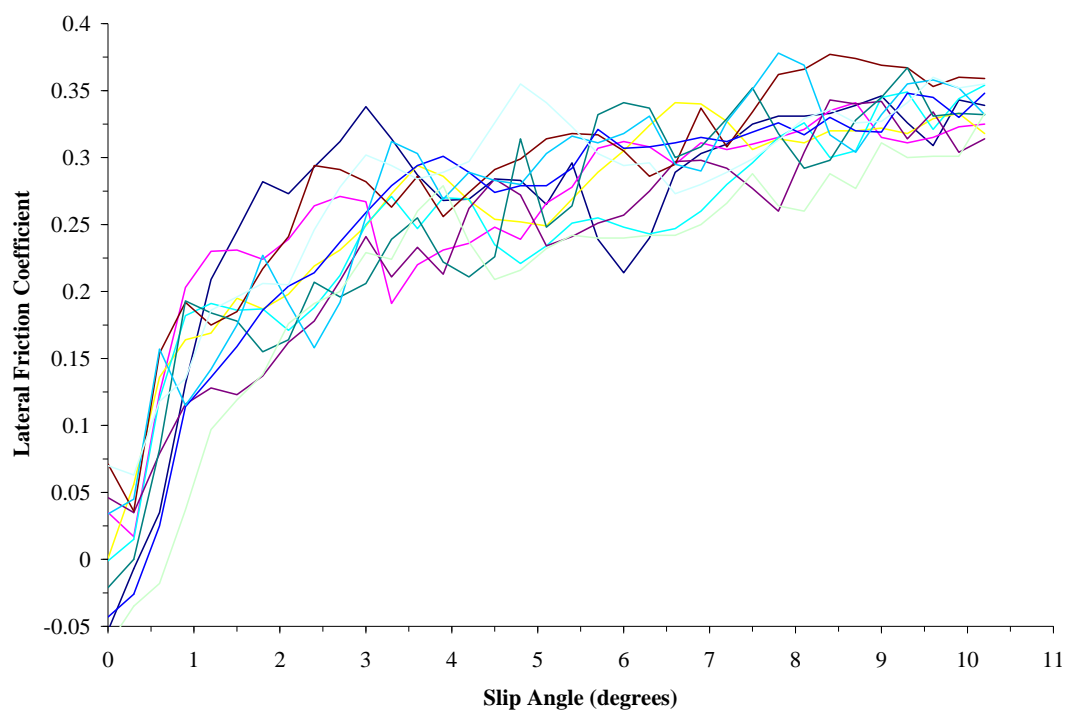
Figure 6. Composite of the 11 individual tests contributing to the dataset for the CIV tire on 2004 packed snow at 283-kPa inflation.
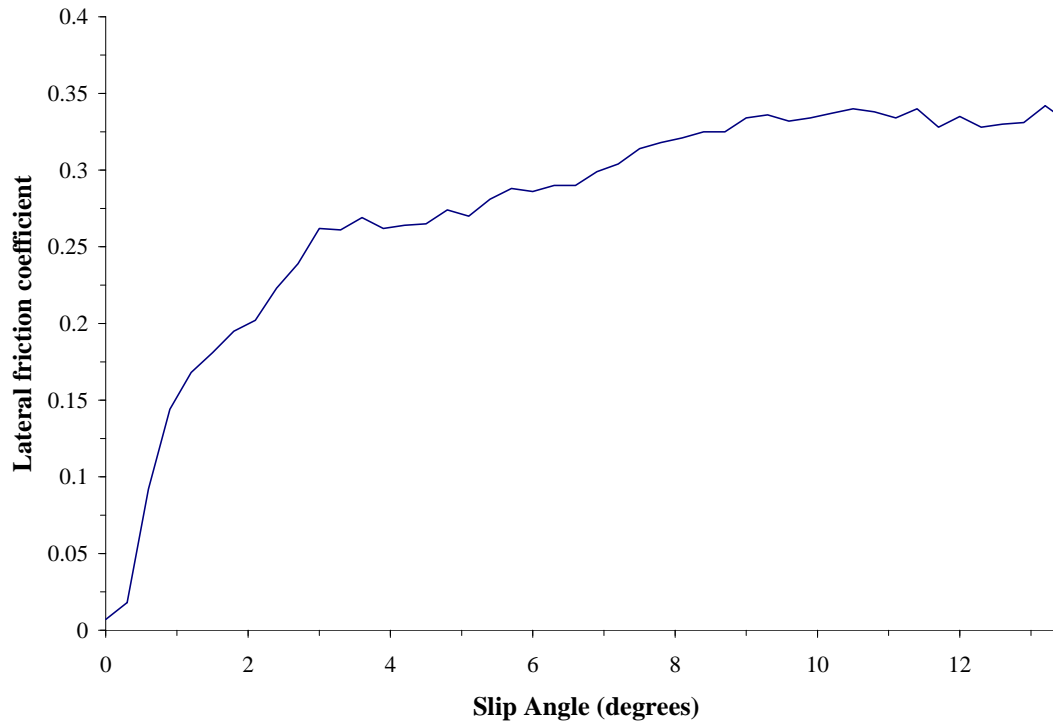

Figure 7. Average of all results for the CIV on 2004 packed snow at 283-kPa inflation.
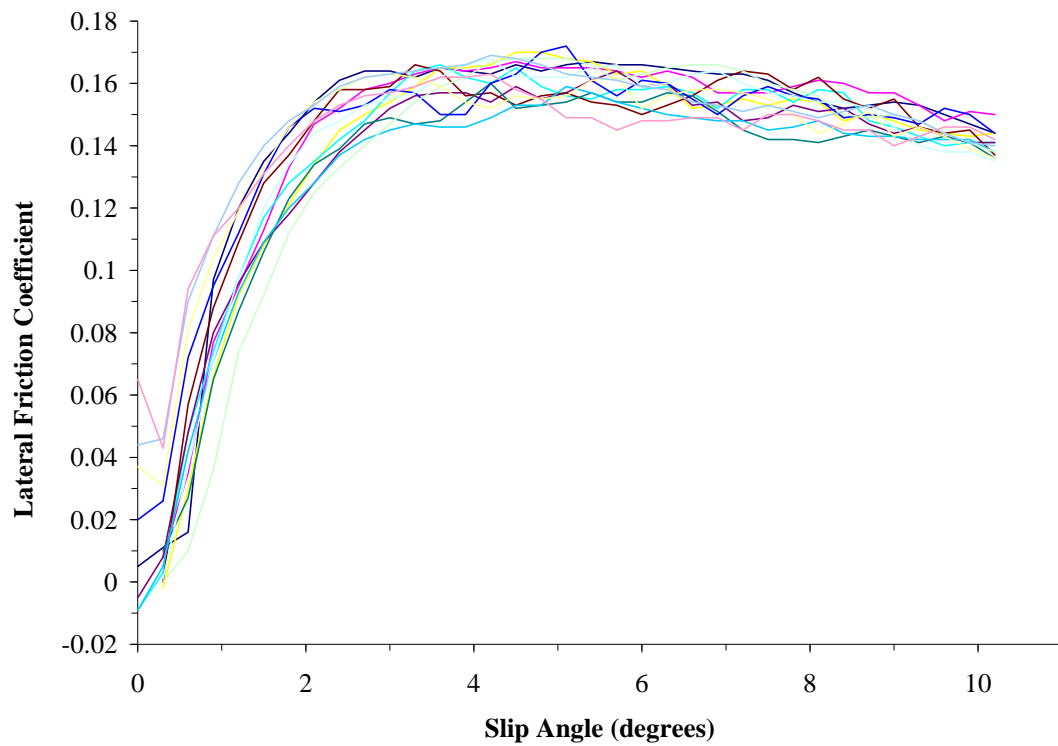
Figure 8. Composite of the 14 individual tests contributing to the dataset for the CIV tire on ice at 152-kPa inflation.
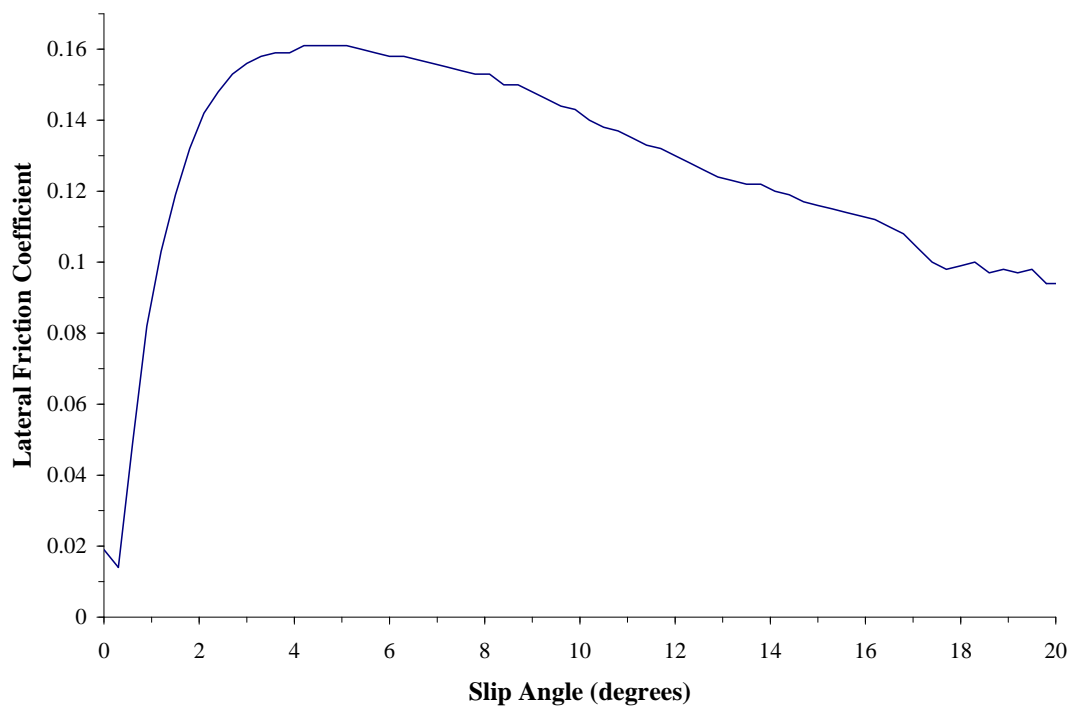

Figure 9. Average of test results for the CIV tire on ice at 152-kPa inflation.

Table 4. Results of lateral traction tests.

Tire	Surface	Tire Pressure (kPa)	Mean Values		Standard Deviations	
			Maximum Lateral Coefficient (ND)	Slip Angle of Max. Lateral Coefficient (degrees)	Maximum Lateral Coefficient (ND)	Slip Angle of Max. Lateral Coefficient (degrees)
CIV (LT235/75R15)	Ice	97	0.155	5.117	0.006	0.870
	Ice	152	0.166	4.457	0.004	0.797
	Ice	283	0.147	4.575	0.007	1.498
	Disaggregated Snow	179	0.331	16.269	0.018	2.146
	Disaggregated Snow	241	0.307	16.230	0.018	1.841
	Packed Snow 04	97	0.375	9.323	0.013	1.178
	Packed Snow 04	152	0.356	9.317	0.014	1.641
	Packed Snow 04	283	0.353	8.945	0.015	1.129
	Packed Snow 05	179	0.397	14.446	0.016	2.741
	Packed Snow 05	241	0.393	17.308	0.015	1.482
HMMWV (37X12.50R16.5)	Ice	138	0.085	2.367	0.004	0.695
	Ice	207	0.081	2.175	0.004	0.800
	Ice	310	0.075	1.255	0.003	0.550
	Disaggregated snow	138	0.327	17.125	0.009	5.687
	Disaggregated snow	310	0.275	18.136	0.014	4.698
	Packed Snow 05	138	0.357	12.927	0.016	5.624
	Packed Snow 05	310	0.378	15.793	0.017	3.718
NATC-SRTT (P195/75R14)	Disaggregated snow	241	0.318	12.788	0.016	2.389
	Packed Snow 05	241	0.419	14.340	0.015	3.885
Passenger Car (225/50R18)	Disaggregated snow	241	0.309	15.960	0.012	1.384
	Packed Snow 05	241	0.426	14.591	0.016	2.776
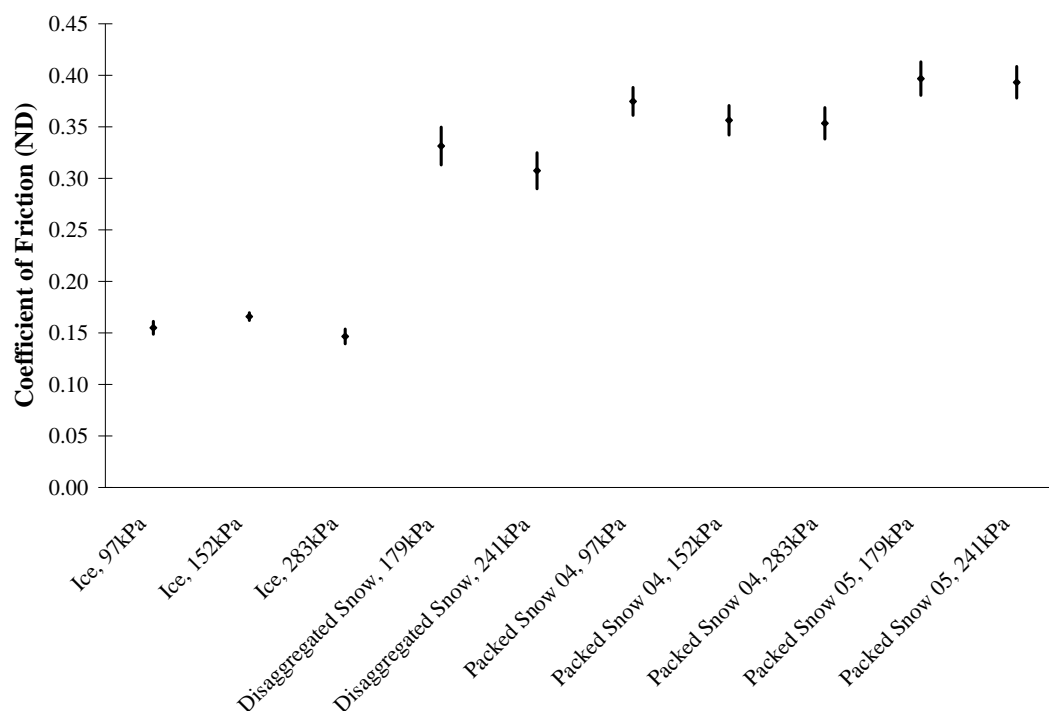
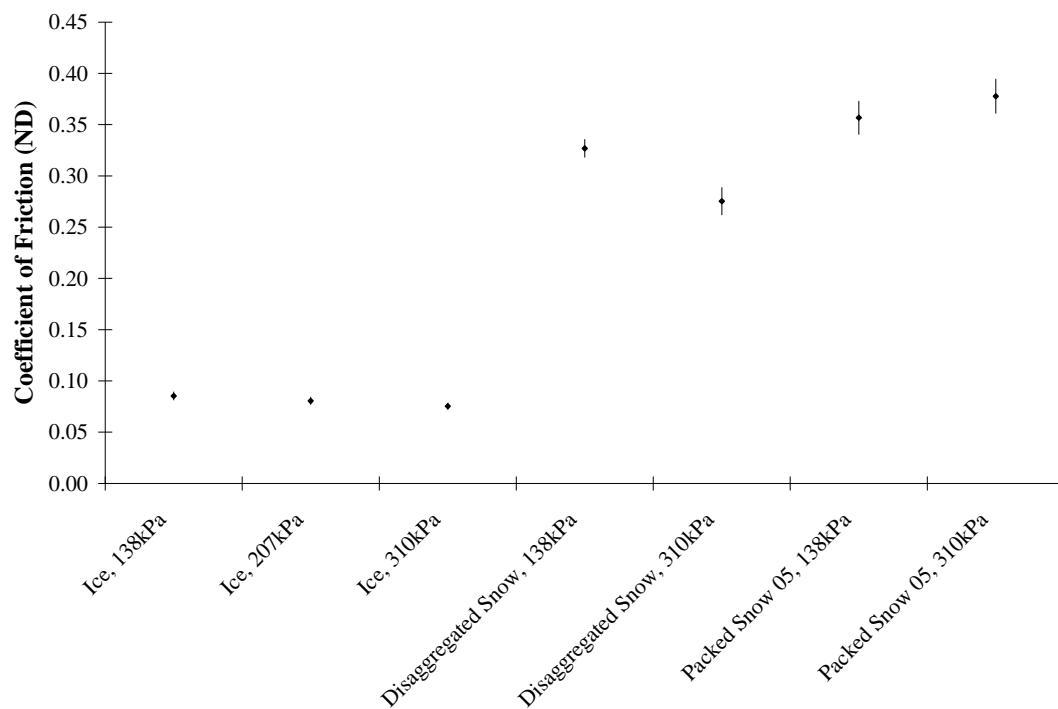Figure 10. Mean of maximum lateral coefficients for the CIV tire. Error bars represent ± one standard deviation.

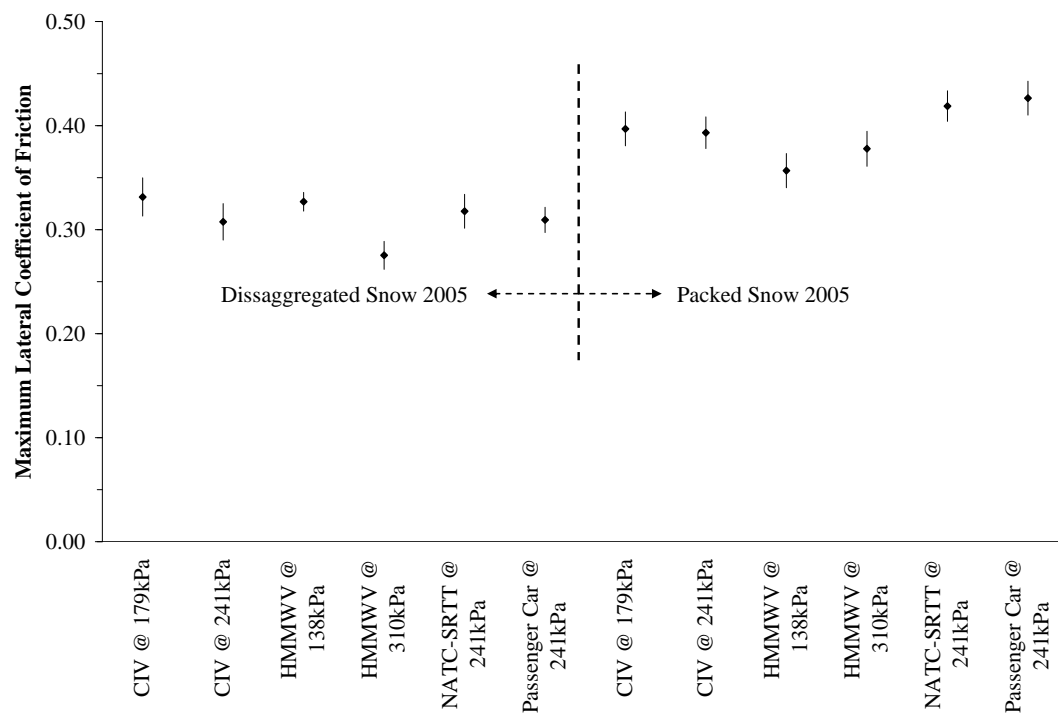Figure 11. Mean of maximum lateral coefficients for the HMMWV tire. Error bars represent ± one standard deviation.

Figure 12. Mean of maximum lateral coefficients for the all tires on the 2005 packed snow and disaggregated snow surfaces. Error bars represent ± one standard deviation.

6   Discussion of Results

Collecting the data with the on-vehicle systems used resulted in offsets in
the lateral coefficient of friction versus slip angle data, so a graph of the
relationship will not necessarily pass through the origin as theory would
predict. We attribute these offsets to characteristics of the on-vehicle sys-
tems, for example, tolerances in the fifth-wheel mechanism that measures
slip angle. To compare data from the various tests it was necessary to
remove those offsets to the extent possible. Our procedure for doing so
involved fitting a hyperbolic tangent function, with an offset term, to each
dataset using the least squares method. The offset determined in this way
was then subtracted from all the data in the set. In arriving at this fit we
used only the data points generated in the initial portion of the lateral fric-
tion coefficient versus slip angle curve, that is, those before the lateral fric-
tion coefficient begins to level out significantly with increasing slip angle.
We also evaluated linear and power function relationships for this pur-
pose, but we felt the hyperbolic tangent provided the best results, largely
because it models the behavior of the lateral coefficient of friction versus
slip angle function properly when transitioning from positive to negative
slip angles and provides a better fit at lower slip angles (before the peak
coefficient lateral friction is reached).

With these offsets removed, the lateral performance of the CIV tire is com-
pared across all test surfaces in Figure 13. Similarly, Figure 14 compares
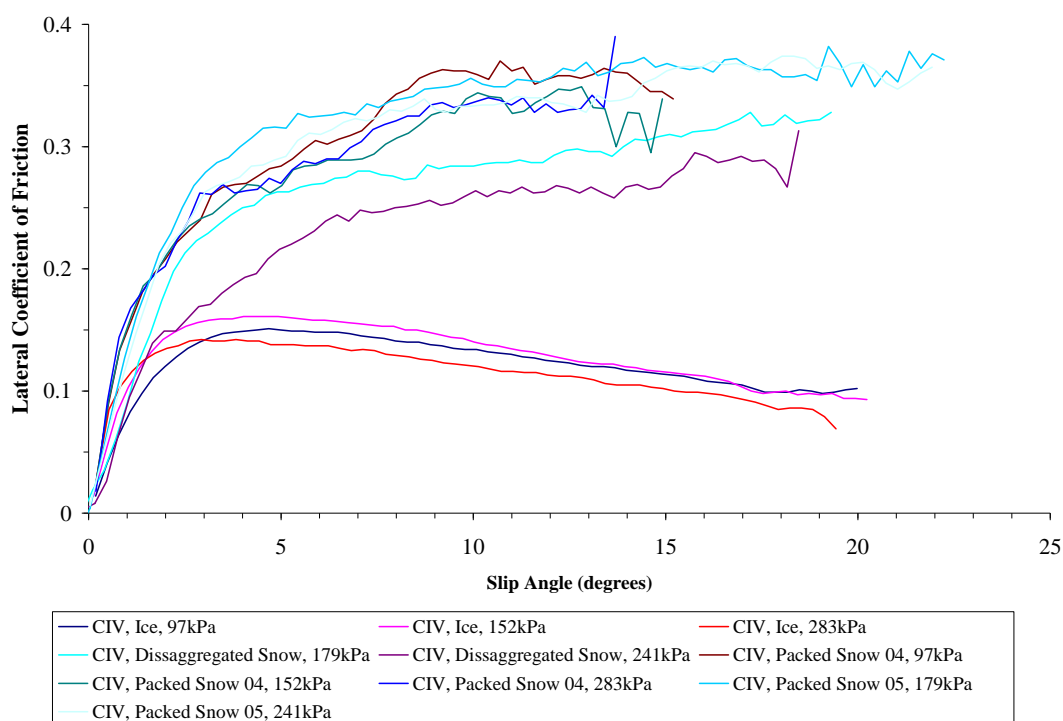the lateral performance of the HMMWV tire on all test surfaces.

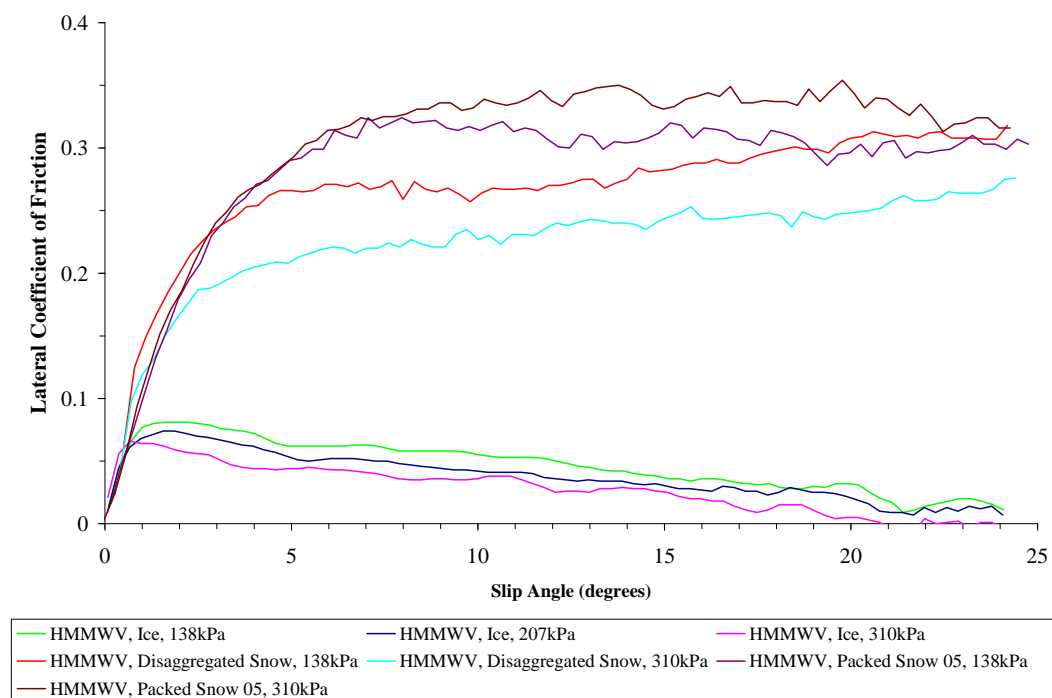Figure 13. Lateral performance of the CIV tire on all test surfaces.

Figure 14. Lateral performance of the HMMWV tire on all test surfaces.

7 Conclusions

The lateral coefficient of friction for both the CIV and HMMWV tires increases rapidly with slip angle from zero slip angle. For the packed and disaggregated snow surfaces, the lateral coefficient of friction appears to asymptotically approach a maximum value with increasing slip angle to slip angles of approximately 15 degrees.

For the ice surface, the initial behavior is similar, but the peak lateral coefficient of friction is reached at low slip angles, normally 2-4 degrees, and then the lateral coefficient of friction falls off significantly.

With respect to peak lateral friction coefficients, the CIV and HMMWV tires behave similarly on each surface with one notable exception: on ice the HMMWV tire develops peak values approximately 50% of those generated by the CIV tire.

Tire pressure impacts were not pronounced when compared to the impacts of the surfaces. In many instances the trends were for higher lateral traction with lower tire pressures, but that was not uniformly true nor were the tire pressure impacts significant when compared to the standard deviations within the datasets themselves (Table 4).

Future plans include the integration of these data with other data CRREL has obtained on winter surfaces, including comparison with the very limited data that are available from other sources. The preliminary results of these efforts are being incorporated in improved mobility models for wheeled vehicles traveling on winter surfaces (Parker et al. 2007).

8   References

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Pacejka, H.B. 2002. *Tire and vehicle dynamics.* Warrendale, PA: Society of Automotive Engineers.

Parker, M., S. Shoop, B. Coutermarsh, K. Wesson, and J. Stanley. 2007. *Verification and validation of a winter driving simulator.* Paper prepared for Joint North American and Asia Pacific Conference of the International Society of Terrain Vehicle Systems (ISTVS), Fairbanks, AK, June 2007.

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14. ABSTRACT

Extending two-dimensional models of tire–vehicle interaction to full three-dimensional functionality requires an understanding of lateral forces on off-road terrain and low-friction surfaces. Experiments were conducted at the Nevada Automotive Test Center using two principal tires—an all-season LT235/75R15, which has been the subject of many tests on the CRREL Instrumented Vehicle (CIV), and a tire used on the military's HMMWV, size 37X12.50R16.5—on ice, packed snow, and disaggregated snow. The tests showed that the lateral coefficient of friction for both tires increases rapidly with slip angle from zero slip angle. For the packed and disaggregated snow surfaces, the lateral coefficient of friction appears to asymptotically approach a maximum value with increasing slip angle to slip angles of approximately 15 degrees. For the ice surface, the initial behavior is similar, but the peak lateral coefficient of friction is reached at low slip angles, normally 2-4 degrees, and then the lateral coefficient of friction falls off significantly. With respect to peak lateral friction coefficients, the two tires behave similarly on each surface with one exception: on ice the HMMWV tire develops peak values approximately 50% of those generated by the CIV tire. Tire pressure impacts were not significant, but the trends were for higher lateral traction with lower tire pressures.

15. SUBJECT TERMS

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	Winter surfaces

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